arXiv:0804.0683v1 [astro-ph] 4 Apr 2008

ACCRETION DISCS, LOW-MASS PROTOSTARS AND PLANETS: PROBING THE IMPACT OF MAGNETIC FIELDS ON STELLAR FORMATION

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Abstract. Whereas the understanding of most phases of stellar evolution made considerable progress throughout the whole of the twentieth century, stellar formation remained rather enigmatic and poorly constrained by observations until about three decades ago, when major discoveries (e.g., that protostars are often associated with highly collimated jets) revolutionized the field. At this time, it became increasingly clearer that magnetic fields were playing a major role at all stages of stellar formation.

We describe herein a quick overview of the main breakthroughs that observations and theoretical modelling yielded for our understanding of how stars (and their planetary systems) are formed and on how much these new worlds are shaped by the presence of magnetic fields, either those pervading the interstellar medium and threading molecular clouds or those produced through dynamo processes in the convective envelopes of protostars or in the accretion discs from which they feed.

1 Introduction

Magnetic fields are known to generate activity in cool stars like the Sun - they are usually attributed to dynamo processes, i.e., to a combination of rotational shearing and cyclonic turbulence in their convective envelopes. As a result, cool spots come and go at their surfaces (for a recent review, see e.g., Berdyugina 2005) and very-hot, low-density plasma is pumped into the closed loops of their large-scale fields. Magnetic fields are also present in a small fraction of warm and hot stars - they likely trace a fossil imprint of the primordial interstellar field

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(trapped and amplified during the cloud collapse) and generate therein a number of spectacular phenomena, such as magnetic wind confinement and abundance anomalies. A more detailed account on magnetic fields of main-sequence stars can be found in Landstreet's contributions (these proceedings).

Eventhough magnetic fields are the engine (or at least the cause) of a large number of significant demonstrations in main-sequence stars (e.g., the strong rotational braking of cool single stars), they do not radically affect their evolution. The situation is however different in pre-main-sequence stars, where magnetic fields are expected to modify drastically not only the contraction of the collapsing molecular cloud, but also the evolution and fate of the protostellar accretion disc, of the newly-born protostar and of its protoplanetary system. Numerous theoretical studies have been published on the various stages of formation process in the presence of magnetic fields (e.g., Mouschovias & Spitzer 1976; Pudritz & Norman 1983; Camenzind 1990; Könígl 1991; Balbus & Hawley 2003; Terquem 2003; Machida et al. 2004; Romanova & Lovelace 2006).

Extensive observational evidence was put forward a few decades ago to demonstrate that magnetic fields are indeed playing a crucial role during the formation stage. For instance, accretion discs are often spatially associated with powerful and highly collimated jets emerging from the disc core and aligned with the disc rotation axis (e.g., Snell et al. 1980), evacuating a significant amount of the angular momentum initially stored in the collapsing cloud; the presence and collimation of these jets can only be explained through magnetic fields (e.g., Pudritz & Norman 1983). Accretion in protostellar discs is also unusually strong, typically orders of magnitude stronger than what molecular viscosity can achieve; again, magnetic fields are invoked as a probable origin for the instabilities boosting the accretion rate (e.g., Balbus & Hawley 2003). Observations also indicate that accretion discs often feature a central gap, and suggest that accretion proceeds from the inner disc ridge towards the central star through dense and discrete funnels; strong magnetic fields on the central protostar can disrupt and evacuate the disc in the innermost regions and connect the star and disc, qualitatively accounting for the observed phenomenon (e.g., Camenzind 1990; Shu et al. 1994). Finally, protostars young enough to feature accretion discs (the classical T Tauri stars or cTTSs) are rotating fairly slowly, more slowly in particular than their discless equivalents (Bertout 1989); theoretical studies proposed that the magnetic coupling between the protostar and its accretion disc is actually responsible for slowing down cTTSs (e.g., Könígl 1991; Cameron & Campbell 1993).

Since these pioneering results, numerous observational studies reported the direct detection of magnetic fields at the surfaces of cTTSs (and in particular in emission lines formed in the accretion regions at funnel footpoints, e.g., Johns-Krull et al. 1999a), within protostellar accretion discs (e.g., Donati et al. 2005) and even within collapsing molecular clouds (e.g., Crutcher 2004). It has also been suggested that magnetic fields could play a significant role in the formation, migration and survival of planets (e.g., Terquem 2003; Fromang 2005; Romanova & Lovelace 2006), especially in the case of close-in giant planets that make up about 25% of the extra-solar planets already discovered. In the follow-

ing sections, we detail what observations have told us and how models tentatively interpret them into a consistent picture of magnetised stellar (and planetary) formation.

2 Magnetic fields and magnetospheric accretion processes of cTTSs

CTTSs typically have ages of a few Myr (ranging from about 1 to 10 Myr) and more or less correspond to the oldest evolutionary stage in which accretion is playing a significant role. (Later stages, e.g., the post T Tauri phase where protostars complete their contraction towards the main sequence with no further accretion from the surrounding environment, are not considered here and are discussed in Bouvier's contribution in the these proceedings).

Among all protostellar objects considered in this paper, cTTSs are the first ones on which magnetic fields were detected directly at their surfaces. These direct detections were diagnosed thanks to the well-known Zeeman effect describing how a magnetic field distorts spectral lines, i.e., how it broadens the unpolarised profiles of magnetically sensitive lines and induces circular (Stokes V) and linear polarisation (Stokes Q and U) signals throughout their widths, depending in particular on the orientation of field lines with respect to the line of sight.

2.1 Magnetic field strengths estimated from line broadening

Early experiments at measuring magnetic fields in cool active stars other than the Sun mostly failed; most of them were using instruments directly inherited from solar physics, estimating line shifts between spectra respectively measured in circular left and right polarisation states and giving access to the average magnetic field component along the line of sight, i.e., the longitudinal field. However, for complex magnetic topologies such as that of the Sun and those anticipated on cool stars, the net longitudinal magnetic field is much smaller, with contributions of opposite polarities mutually cancelling out.

Investigations of the differential broadening of unpolarised spectral lines with different magnetic sensitivities demonstrated unambiguously that magnetic fields are indeed present at the surfaces of cool stars; magnetic broadening being mostly insensitive to the field orientation, contributions from regions of opposite polarities no longer mutually cancel in the integrated signal from the whole star. This method yields an estimate of the relative surface area covered with magnetic fields, along with an average magnetic intensity (sometimes a rough distribution of magnetic intensities) within these magnetic regions. It allowed the majority of the direct field detections at the surfaces of cTTSs, using near IR spectral lines to provide higher sensitivities (e.g., Johns-Krull et al. 1999b; Johns-Krull 2007; note also the first observational hint on the presence of such magnetic fields reported by Basri et al. 1992).

Magnetic field strengths of 2–3 kG, i.e., significantly larger (by typically a factor of 2) than what thermal equipartition predicts, are measured in the photospheres of most cTTSs (Johns-Krull 2007). Moreover, the estimated field strengths correlate

very poorly with those predicted by current magnetospheric models when assuming that the slow rotation is indeed due to star/disc magnetic coupling (Königl 1991; Cameron & Campbell 1993; Shu et al. 1994; Long et al. 2005). These results suggest that the slow rotation of cTTSs could actually be due to some other braking mechanism, e.g., to a strong magnetised mass-loss rate through which large loads of angular momentum could escape from the star. A similar conclusion was also reached on theoretical arguments; according to the authors, the wind pressure could be strong enough to blow open most field lines larger than 3 R_* and thus to prevent magnetic coupling to operate efficiently at distances large enough to explain the slow rotation of cTTSs (Safier 1998; Matt & Pudritz 2004).

Field strengths of cTTSs estimated from line broadening techniques also correlate very poorly with rotation rate conversely to what is expected from dynamo models (e.g., Chabrier & Küker 2006; Dobler et al. 2006; Browning 2008), leading the authors to conclude that they are more likely to be fossil fields rather than dynamo fields (Johns-Krull 2007). However, cTTSs being fully convective, putative fossil fields in their interiors are not expected to survive for timescales much longer than a few 100 yrs at most (e.g., Chabrier & Küker 2006). Moreover, dynamo models in fully convective stars are still rather uncertain (and even potentially discrepant) at the moment, with some predicting that purely non-axisymmetric fields should be generated without any differential rotation (Chabrier & Küker 2006) and others claiming that differential rotation should be present along with mostly axisymmetric fields (Dobler et al. 2006).

We come back on these issues below.

2.2   *Magnetic topologies derived from time-resolved spectropolarimetry*

Since 1990, various studies demonstrated that polarisation signatures in spectral lines of cool stars, although often very weak, are actually detectable provided that full Zeeman signatures (rather than longitudinal fields values only) are recorded, and that specific and optimised instrument, observing procedure and reduction software are used (Donati et al. 1997). While this latter technique remains insensitive to the small magnetic bipolar groups potentially present at the surface of the star (with nearby opposite polarities mutually cancelling their respective circular polarisation signatures), it can however yield key information such as how much fractional magnetic energy is stored within large and medium spatial scales, and how the field decomposes into its axisymmetric and non-axisymmetric modes, or into its poloidal and toroidal components. In this respect, it represents a genuinely new and very powerful tool for studying dynamo processes of active stars in general, and of cTTSs in particular.

High-resolution spectropolarimeters, and in particular the new generation instruments ESPaDOnS (mounted on the 3.6m Canada-France-Hawaii Telescope - CFHT - atop Mauna Kea in Hawaii) and NARVAL (mounted on the 2m Telescope Bernard Lyot - TBL - atop Pic du Midi in France) are used for such studies Donati et al. 1997, 2006c; they consist of an achromatic polarimeter mounted at the Cassegrain focus of a telescope, fiber feeding a bench-mounted high-resolution

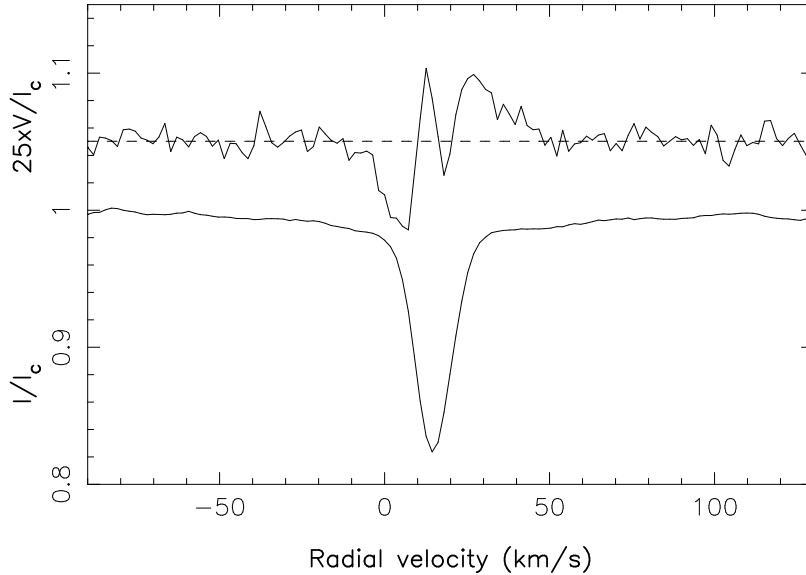LSD profiles of BP Tau, ESPaDOnS@CFHT, 2004 Sep. 03

Fig. 1. LSD circular polarisation Zeeman signature from the photospheric lines of BP Tau, as derived from ESPaDOnS data

échelle spectrograph on which both orthogonal components of the selected polarisation state can be simultaneously recorded as interleaved échelle spectra on the CCD detector. Given that typical Zeeman signatures from cool active stars are rather small (Donati et al. 1997), detecting them usually requires the extraction of the relevant information from as many lines as possible throughout the entire spectrum, using cross-correlation type tools such as Least-Squares Deconvolution (Donati et al. 1997). Up to 8,000 lines can be used in the domain of ESPaDOnS, yielding average Zeeman signatures with an equivalent signal to noise ratio boosted by several tens compared to that of a single average spectral line (see Fig. 1).

Using spectropolarimetry, strong circularly polarised Zeeman signatures were detected in narrow emission lines forming at the base of accretion funnels (eg the He I D$_3$ line at 587.6 nm), demonstrating that magnetic fields indeed actively participate to the accretion processes (Johns-Krull et al. 1999a). Further observations collected across the rotation cycles of a few cTTSs (Valenti & Johns-Krull 2004; Symington et al. 2005) show that these Zeeman signatures vary smoothly with rotation, indicating that the large-scale magnetic geometry (anchored in kG field regions at the stellar surface) is rather simple, well-ordered and mostly axisymmetric with respect to the stellar rotation axis; it also suggests that it is mostly stable on time scales of several years. These initial studies however failed

at detecting Zeeman signatures in photospheric lines of cTTSs (Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004) down to a level of a few hundred G. This non-detection was at first rather mysterious given the simple large-scale magnetic topologies derived from Zeeman signatures of narrow emission lines; prominent circular polarisation signals are indeed expected in photospheric lines if the large-scale field is simple and well-ordered, and only highly tangled magnetic fields can remain totally undetected through spectropolarimetry.

Detailed spectropolarimetric monitoring was recently carried out on 2 cTTSs, namely BP Tau and V2129 Oph (Donati et al. 2008, 2007). BP Tau is less massive than the Sun (about 0.7 $M_\odot$) and is still fully convective, whereas V2129 Oph is more massive than the Sun (and at about 1.35 $M_\odot$ is twice as massive as BP Tau) and has already started to build up a radiative core. Both have similarly long rotation periods (7.6 and 6.4 d respectively), similar radii (2.0 and 2.4 $R_\odot$ respectively) and average accretion rates (3 and 1×10^{-8} $M_\odot$ yr^{-1} respectively). Both were followed over the full rotational period, at 2 different epochs in the particular case of BP Tau. In both of them, strong Zeeman signatures from narrow emission lines were detected and found to vary smoothly with rotation rate, in complete agreement with previous results (Valenti & Johns-Krull 2004; Symington et al. 2005). In addition, weaker (though still very clear) Zeeman signatures were detected in photospheric lines (eg, see Fig. 1); their complex shape however confirms that the surface field topology on both BP Tau and V2129 Oph is more complex than a simple dipole.

Using Zeeman-Doppler imaging, phase-resolved spectropolarimetric data sets can be turned into vector images of magnetic topologies at stellar surfaces; the magnetic field is decomposed into its poloidal and toroidal components and expressed as a spherical harmonics expansion, whose coefficients are fitted to the data using maximum entropy image reconstruction (Donati & Brown 1997; Donati et al. 2006b). This method is found to be efficient at recovering large-scale magnetic topologies, even in the case of slow rotators (Donati et al. 2006b) like cTTSs.

A consistent model of the large-scale magnetic field was obtained for both stars, fitting simultaneously the Zeeman signatures from photospheric lines and narrow emission lines, under the basic assumption that both sets of Zeeman signatures correspond to spatially distinct regions at the surface of the stars (with narrow emission lines tracing accretion spots at funnel footpoints mostly, whereas photospheric lines are tracing non-accreting regions only). The large-scale magnetic topologies derived for BP Tau and V2129 Oph (see Figs. 2 and 3) show that the field is significantly more complex than a dipole, involving in particular a strong octupolar component (1.6 and 1.2 kG for BP Tau and V2129 Oph respectively) and a weaker dipole component (1.2 and 0.3 kG respectively). In both cases, the reconstructed magnetic fields are dominantly poloidal. Accretion is found to occur mostly in a high-latitude region covering a few percent of the stellar surface, coinciding with a dark spot at photospheric level and hosting intense unipolar magnetic fields (3 and 2 kG respectively). The magnetic topologies in non-accreting regions is more complex, featuring closed magnetic loops linking nearby regions of opposite polarities (see Figs. 2 and 3).
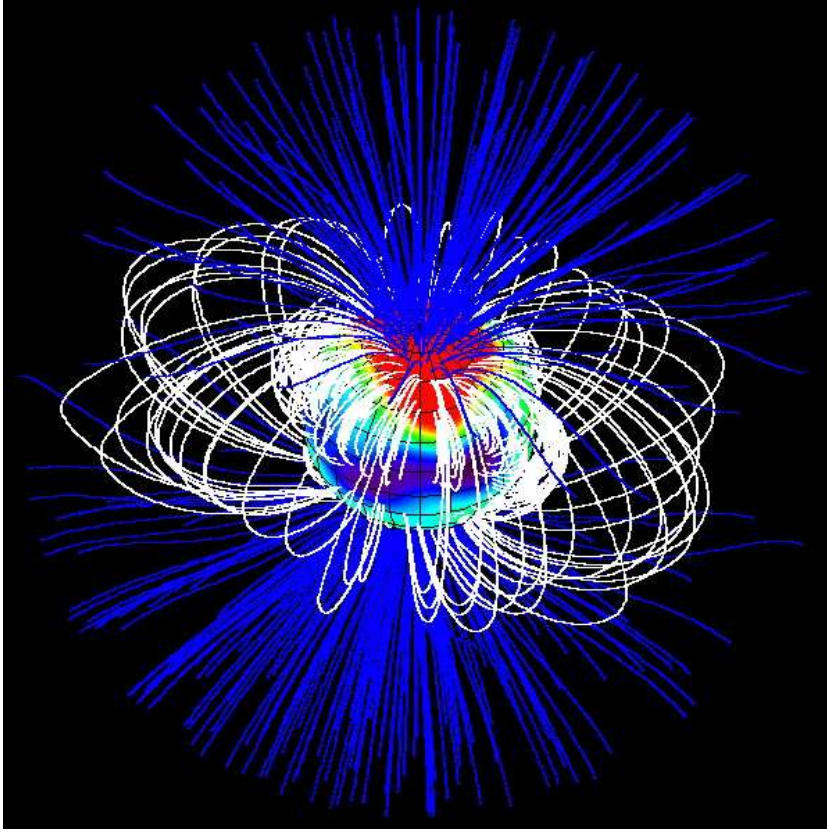
Fig. 2. Magnetospheric topology of the cTTS BP Tau, derived from a potential field extrapolation of the Zeeman-Doppler imaging map and the spectropolarimetric data set (Donati et al. 2008). The colour patches at the surface of the star represent the radial component of the field (with red and blue corresponding to positive and negative polarities); open and closed field lines are shown in blue and white respectively.

The large-scale magnetic topologies derived for BP Tau and V2129 Oph are reminiscent of those found in older active stars, i.e., including strong, long-lived, roughly-axisymmetric dipolar components when the star is fully convective (Donati et al. 2006a; Morin et al. 2008) like BP Tau, and a weaker dipolar component when the star is only partly convective (e.g., Donati et al. 2003) like V2129 Oph. Although this is certainly too early to conclude about the origin of the field in cTTSs (given that only 2 stars have been spectropolarimetrically monitored up to now), this similarity nevertheless suggests that dynamo processes (undoubtedly producing the fields of more evolved stars) can probably also be held responsible for generating the magnetic topologies of cTTSs. Given that different types of dynamo processes are expected to operate in partly- and fully-convective stars on the one hand, and
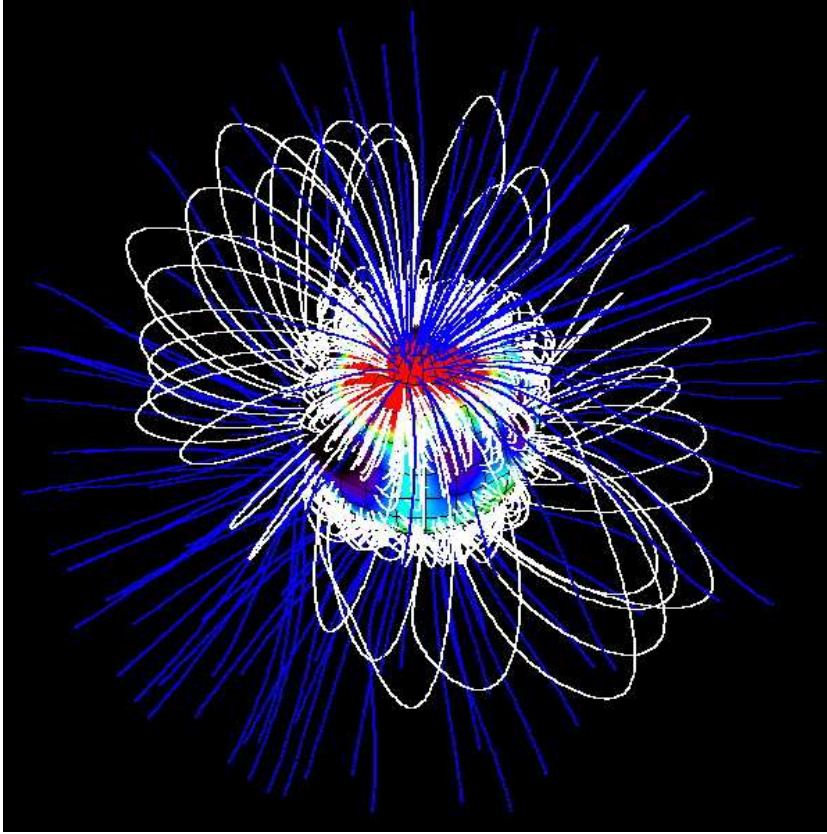
Fig. 3. Same as Fig 2 for the cTTS V2129 Oph (Donati et al. 2007).

that dynamo processes are likely saturating in cTTSs already (despite their low rotation rate) on the other hand, the poor correlation of magnetic characteristics with rotation rate in cTTSs (Johns-Krull 2007) can probably not be used as strong evidence that fields of cTTSs are not dynamo generated.

Detailed magnetospheric modelling using potential field extrapolation (assuming that the field gets radial beyond a given distance from the star, Jardine et al. 2006; Gregory et al. 2006a,b) was achieved for both stars (Jardine et al. 2008; Gregory et al., in preparation). With this modelling, one can investigate which magnetic lines are open (wind-bearing) field lines, which are closed (X-ray bright) field lines and which are passing through the equatorial plane and are thus available to accrete material from the disc. We find that matching the observations, and in particular the fact that accretion funnels are anchored at high latitutes, requires disc material to accrete from a distance of at least 5–7 $R_\star$ for both stars, i.e., close to the Keplerian corotation radii. It demonstrates in particular that magnetic fields of BP Tau and V2129 Oph (and probably most cTTSs as well)

are truly able to couple to their accretion disc beyond 3 $R_\star$ (conversely to what theoretical studies claimed, e.g., Safier 1998) and up to at least 7 $R_\star$. Magnetic coupling between the star and its accretion disc therefore still appears as a viable option for explaining the slow rotation of cTTSs; looking for potential correlations between the strengths of the observed dipolar components (rather than the average surface field strengths, as in Johns-Krull 2007) with those predicted by theories (to enforce corotation with the Keplerian disc at the observed rotation period) will ultimately tell whether this is indeed the case.

A large number of multi-D numerical simulations were carried out in the last few years to investigate the physics and dynamics of magnetospheric accretion, as well as to test whether magnetospheric coupling is indeed a viable option in practice to extract angular momentum from cTTSs and slow down their rotation (e.g., Romanova et al. 2003, 2004; von Rekowski & Brandenburg 2004; Long et al. 2005, 2007, 2008; Bessolaz et al. 2008). Most simulations are assuming that the magnetic field is a dipole, either aligned or tilted with respect to the rotation axis, and that there is no disc field per se (except in von Rekowski & Brandenburg 2004); more complex field configurations (though not quite as complex as those observed on BP Tau and V2129 Oph) were also investigated in the most recent studies (Long et al. 2007, 2008). The various accretion patterns that the simulations recover (e.g., Romanova et al. 2003, 2004; Long et al. 2007, 2008) are in qualitative agreement with observations.

Concerning the magnetic coupling of the star with its accretion disc, the problem is apparently still open. One potential issue concerns the ability of the magnetic field to efficiently link the star to the disc despite field lines spontaneously opening as a result of the difference in the angular velocities of footpoints; another problem is whether the star is actually spun-up or down as a result of the competition between accretion, wind and magnetic coupling (accretion contributing to spinning up the star while the magnetic and wind torques participating in slowing it down). While some authors find that the star is actually spun-up (e.g., von Rekowski & Brandenburg 2004; Bessolaz et al. 2008), some authors conlude that the opposite happens (e.g., Long et al. 2005). Obviously more work is needed on this issue to be able to conclude about the disc-locking mechanisms, requiring in particular 3D simulations with realistic field geometries.

2.3 Constraints on magnetic topologies from indirect activity tracers

Investigating magnetic fields of protostars is also possible (though admittedly more ambiguous) through indirect proxies, like for instance activity tracers usually associated with magnetic fields in cool active stars, e.g., spots darker (or brighter) than the surrounding photosphere, photometric variability (e.g., due to the presence of surface spots carried in and out of the observer's view by rotation), rotational modulation of photospheric spectral lines (e.g., induced again by spots travelling onto the stellar disc), emission in narrow and broad emission lines (e.g., due to the presence of hot chromospheric and coronal plasmas, or to hot material at the footpoint of accretion funnels), radio emission (due to synchrotron electrons
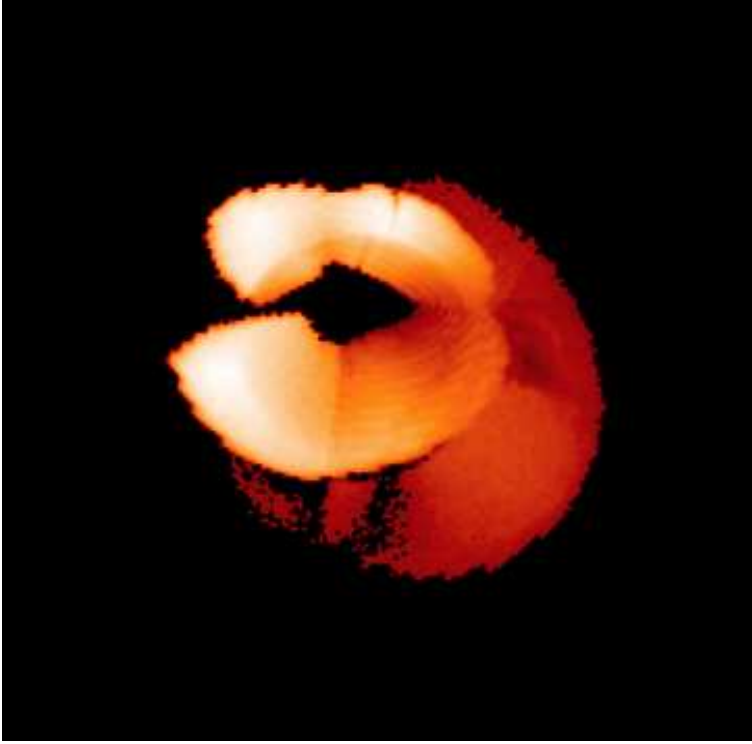
Fig. 4. X-ray image of the cTTS V2129 Oph, derived from the magnetospheric map of Fig. 3 (Jardine et al. 2008).

spiralling about the large-scale magnetic loops), UV and X-ray emission (with spectral lines from highly ionised species formed in the chromosphere, corona and accretion shocks).

Multicolour photometric monitorings of cTTSs first demonstrated that young protostars were indeed active (Bouvier & Bertout 1989), with activity demonstrations similar to those seen in more evolved cool stars. With simultaneous photometric and spectroscopic monitoring carried over several rotation cycles (e.g., Bouvier et al. 2007a,b), one can obtain indirect evidence on how magnetospheric accretion operates and how the magnetic field controls both the accretion funnels and the inner disc rim. In the particular case of the cTTS AA Tau, the magnetic field is again found to be able to connect to the disc up to a distance of 9 $R_\star$ and even to warp it significantly and produce periodic partial eclipses of the central star as it rotates (AA Tau is viewed almost edge-on from the Earth, allowing us to probe in a unique way the accretion region close to the star).

The advent of the first X-ray spacebound spectrographs Chandra and XMM allowed the collection of low-resolution X-ray spectra of cTTSs and revealed a wealth of new characteristics of cTTSs in relation to their magnetic fields. In

particular, the Chandra Orion Ultradeep Project (COUP, monitoring the Orion Nebula Cluster continuously with Chandra for 13 d, Feigelson et al. 2005), and the XMM Extended Survey of the Taurus molecular cloud (XEST, Güdel et al. 2007a) have brought a tremendous amount of new material. Among various results, they show for instance that cTTSs exhibit both very hard X-ray emission - corresponding to temperatures of 10–100 MK and associated with coronal activity from medium-scale magnetic loops - as well as relatively softer emission - corresponding to temperatures of a few MK and associated with the accretion shocks at the base of the large-scale magnetic loops linking the star to the disc. They also show that cTTSs are comparatively less luminous in X-rays than non-accreting stars of similar characteristics, as the possible result of X-rays from coronal regions being strongly absorbed by the dense gas of accretion columns (Gregory et al. 2007). Another very recent result is the discovery of largely unabsorbed soft X-rays from jet-driving protostars that also emit heavily-absorbed hot (and presumably coronal) X-rays (Güdel et al. 2007b); since the soft component cannot originate close to the star (as it would otherwise be absorbed in the same way as the hot coronal component), it suggests that shocks in jets are also contributing to the X-ray emission.

Using 3D magnetospheric maps of cTTSs obtained from spectropolarimetric monitoring and potential field extrapolation (see above), it is possible to obtain coronal models of cTTSs matching their X-ray properties (see Fig. 4, Jardine et al. 2008) and find out the location and extent of coronal loops as well as the densities of the associated plasma; it is even possible to predict the shape and amplitude of X-ray light curves that their coronal and accretion topologies produce. Simultaneous spectropolarimetric and X-ray monitoring thus appears as an optimal way of getting consistent models of cTTS magnetospheres in the future.

3 Accretion discs, jets and protoplanetary systems

Protostellar accretion discs may also host magnetic fields. In fact, they are likely to be the place where interstellar magnetic fields transit towards stellar cores to form magnetic stars with genuine fossil fields (like those of massive stars, see Landstreet, these proceedings). Magnetic fields are also likely playing a key role in boosting disc accretion rates through instabilities (e.g., Balbus & Hawley 2003) and are the main ingredient with which discs succeed at launching powerful winds/jets and expel a significant fraction of their initial mass and angular momentum (for a recent review on this subject, see Pudritz et al. 2007).

Magnetic fields were detected in the external regions of a few protostellar accretion discs (Hutawarakorn & Cohen 2003), demonstrating that these discs are indeed intrinsically magnetic as predicted. However, very little is known about their actual fields, in particular in the innermost regions of discs (within 1 au of the central protostar) where fields are presumably strongest and from which jets are fired.

Investigating magnetic fields of accretion discs is however not easy. Accretion discs of cTTSs are relatively faint and difficult to observe, at least in the optical

domain, given the strong contrast and small angular separation with the central protostar - especially the core regions. An interesting option is to study FUOrs, a class of young (about 0.1 Myr) protostellar accretion discs undergoing so strong an outburst that the central protostar is completely outshined by the flaring disc, even at optical wavelengths. FU Ori itself is by far the best target for such investigations, with optical wavelengths offering a direct window to the innermost disc regions (within 0.1 au) through a rich absorption spectrum featuring a few thousand lines. Exploratory observations with ESPaDOnS (Donati et al. 2005) demonstrate that strong magnetic fields are indeed present, producing small but detectable Zeeman signatures in photospheric lines.

A detailed analysis of the unpolarised and circularly polarised LSD profiles indicate that the disc density and magnetic field are mostly axisymmetric (given the low level of temporal variability in LSD profiles) and that a significant fraction of the disc plasma is rotating at strongly sub-Keplerian velocities (given the flat-bottom shape of line profiles, see Fig. 5). Decomposing the observed Zeeman signature into its antisymmetric and symmetric components (with respect to the velocity rest frame) provides direct access to the vertical and azimuthal components of the (assumed axisymmetric) field; the magnetic field apparently concentrates into the slowly rotating disc plasma, includes a dominant vertical component (of about 1 kG) and a significant azimuthal component (about half as large).

The first important conclusion is that the field we detect is likely not produced through a disc dynamo; disc dynamos are indeed expected to generate dominantly toroidal field configurations in inner disc regions (Brandenburg et al. 1995; von Rekowski et al. 2003). Our result is in much better agreement with disc field topologies derived from numerical collapse simulations of magnetic clouds, assuming that the field is primordial and mostly advected by the collapsing plasma (e.g., Machida et al. 2004; Banerjee & Pudritz 2006; Hennebelle & Fromang 2008); we therefore conclude that the origin of the field is likely fossil. The second conclusion is that primordial magnetic fields are obviously able to survive the cloud collapse without being entirely dissipated by turbulence; while many different models (e.g., the fossil field theory usually invoked to explain the magnetic fields of massive stars) already assumed long ago that it was likely the case, it is nevertheless reassuring to obtain definite evidence that this is indeed what happens.

The third conclusion is that the magnetic topology threading the innermost regions of FU Ori is grossly compatible with those predicted by collimated jet theories (e.g. Ferreira & Pelletier 1995). However, the strong slow down that the magnetic plasma undergoes comes as a definite surprise; it could be one reason for which FU Ori is apparently unable to launch a jet (while FUOrs are usually known for launching jets efficiently). More generally, the question of why protostars and their accretion discs are not all associated with collimated jets remain open. One possibility is that the magnetic topologies of accretion discs (or even the structure of the disc itself) are sometimes not adequate for launching jets (e.g., Ferreira et al. 2006); while a single example is obviously not enough to conclude, observations of FU Ori suggest that this is probably not the only reason. Another
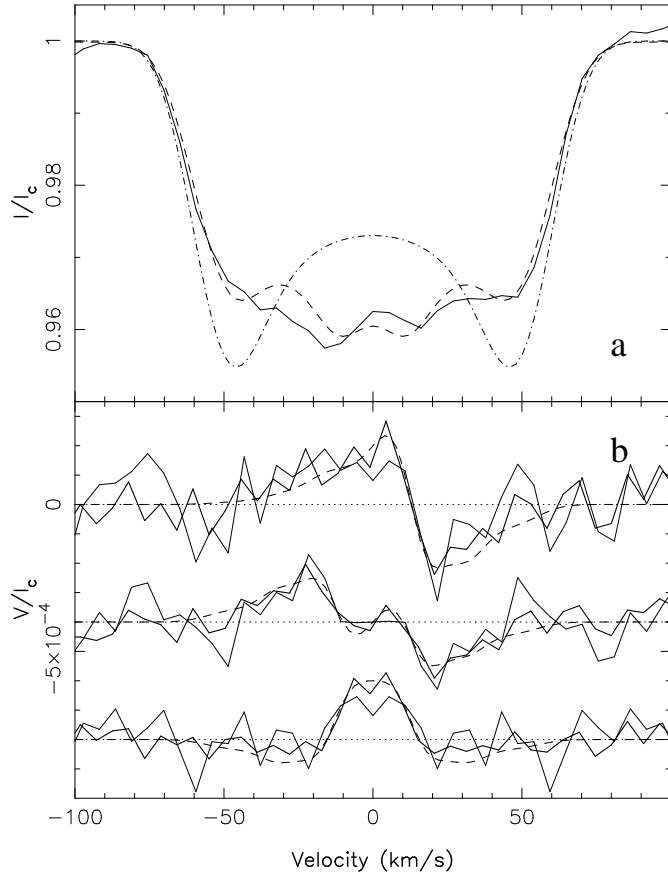
Fig. 5. Unpolarised and circularly polarised LSD profiles of FU Ori. a: Observed Stokes I profile (solid line) along with a Keplerian disc model (dash-dot line) and a non-Keplerian model (with 20% of the disc plasma rotating at strongly sub-Keplerian velocities, dashed line). b: Observed Zeeman signature (top curve) split into its antisymmetric and symmetric components (middle and bottom curves, shifted by -4 and -8×10^{-4}) respectively characterising the vertical and azimuthal axisymmetric magnetic fields. The model (dashed line) requires the slowly rotating disk plasma to host a 1 kG vertical field plus a 0.5 kG azimuthal field. (From Donati et al. 2005).

potentially important factor is the orientation of the disc (and of its rotation axis) with that of large-scale interstellar magnetic field; protostars in Taurus are indeed found to be more successful at launching jets when their accretion discs are perpendicular to the interstellar field (Ménard & Duchêne 2004, see also Ménard, these proceeding). A third option is that the magnetic field of the protostar also plays a significant role in jet launching mechanisms; observing magnetic configurations in

a sample of accretion discs and cTTSs featuring different accretion rates and out-
flow properties, and looking for potential correlations between critical parameters,
may ultimately provide quantitative constraints on this issue.

Observing magnetised accretion discs can also yield information on how giant
exoplanets form, migrate inwards (as a result of the gravitational torque they suffer
from the disc) and survive the migration to end up as one of the numerous close-
in giant exoplanets detected in the last decade. Are these planets stopped by a
toroidal magnetic field (Terquem 2003)? Or do they stop as a result of their falling
within the central magnetospheric gap of cTTSs (Romanova & Lovelace 2006)?
This is clearly an open question at the moment; the recent detection of a close-in
giant exoplanet orbiting TW Hya within the inner disc rim (Setiawan et al. 2008)
suggests that the second option is very attractive and confirms that the migration
process occurs mostly (as expected) as part of the formation process. Monitoring
accretions discs on timescales comparable to their Keplerian periods (about 15 d
at 0.1 au) can yield further information, e.g., by identifying density gaps in accre-
tion discs and their potential relation with magnetic fields. Periodic signals have
already been identified from the unpolarised spectrum of FU Ori and tentatively
attributed to the presence of close-in giant planets (e.g., Clarke & Armitage 2003).
Such data could also give some direct constraints on whether magnetic fields are
truly able to modify planet formation by inhibiting fragmentation (e.g., Fromang
2005; Hennebelle & Teyssier 2008).

4   Observing the magnetic collapse?

Magnetic fields are expected to play an even greater role at earlier stages of stel-
lar formation, even before the protostar is actually formed (i.e. at ages lower
than about 0.1 Myr) as clearly evidenced by several very recent numerical sim-
ulations (Machida et al. 2004; Banerjee & Pudritz 2006; Hennebelle & Fromang
2008). Eventhough these simulations still need to be improved with respect to
physical realism (e.g., by no longer assuming ideal MHD) and to be carried out
over longer time scales (up to at least the formation of a second stellar core, i.e., at
an age of about 0.1 Myr), they already provide a wealth of impressive and promis-
ing results; in particular, they all agree on the fact that magnetic fields similar
to those observed in molecular clouds (i.e., corresponding to a mass-to-flux over
critical mass-to-flux ratio of a few, e.g., Crutcher 2004; Hennebelle & Fromang
2008) indeed have a drastic influence on the collapse, e.g., by removing from the
collapsing cloud the vast majority of the initial angular momentum content.

Direct observations of collapsing clouds demonstrating this and confirming the
theoretical predictions are difficult and rare, but are progressively becoming avail-
able; for instance, recent radio observations (Girart et al. 2006) showed that the
magnetic field of a collapsing cloud exhibits the typical hourglass shape that the-
oretical star formation models predict. Observations of molecular clouds with
ALMA should bring lots of similar examples in the near future, to which numeri-
cal simulation results will be directly comparable.

In the meantime, we can try to extrapolate what simulations predict and see

how it matches what we know of magnetic stars, especially with respect to the quantities that are likely to be the most affected by magnetic fields like magnetic fluxes, angular momentum and binarity (e.g., Hennebelle & Fromang 2008; Hennebelle & Teyssier 2008). For low mass stars, simulations predict that newly-born protostars should start their life with magnetic fields of 0.1–1 kG and rotation rates of 0.1–2 d (Machida et al. 2007). These predictions however neglect the fact that dynamo fields are likely to be also present (and even dominant, see above) in protostars, and that magnetic coupling with the disc at the cTTS phase is probably slowing down the star significantly. They are nevertheless very interesting to estimate what these quantities should typically be before protostars start to build up strong dynamo fields and interact with their accretion discs; it suggests for instance that the star-disc magnetic coupling is indeed slowing down (rather than spinning up) the protostar to dissipate the angular momentum excess that simulations predict.

Another class of magnetic stars on which similar simulations are worthwhile are massive magnetic stars (see Lanstreet, these proceedings), supposed to host mostly fossil fields (having skipped a fully convective stage that would have erased the initial magnetic imprint) and to have preserved most of their initial angular momentum (their evolution timescales being shorter than their magnetic braking timescales in most cases). Extrapolating the results of collapse simulations suggests that stars formed in highly magnetic clouds should show (in addition to a higher magnetic flux) a significantly lower than average angular momentum, being formed mostly from material nearby the rotation axis with little specific angular momentum (with the cloud gas following field lines in a mostly cylindrical, rather than spherical, collapse, e.g. Hennebelle & Fromang 2008); moreover, they should be much less prone to end up in binary systems, since magnetic fields are apparently very efficient at inhibiting fragmentation (Hennebelle & Teyssier 2008). Observations indicate indeed that highly magnetic stars with masses larger than about 2 $M_\odot$ are rotating very much slower than their non-magnetic equivalents and that the binarity frequency is considerably reduced (by more than a factor of 2) for this sample, with no convincing explanation found since the intial discovery about 35 yr ago (Abt & Snowden 1973). Despite being no more than a qualitative match, this result is nevertheless promising and, if confirmed, could potentially establish more firmly the fossil nature of magnetic fields in massive stars.

5 Conclusion and prospects

In the last few decades, our understanding of stellar formation has greatly improved. In particular, it made clear that magnetic fields are playing a major role at almost all stages of the formation process, from the very beginning of the collapse, to the formation and evolution of the accretion disc, to the production of winds and outflows, to the formation of the star and its planetary system. Despite this progress, a lot of questions remain unanswered. Quoting some of the main ones:

- How much angular momentum and magnetic flux is dissipated during the cloud collapse, and what is the origin of the accretion disc field?
- How does magnetospheric accretion control the angular momentum and how much does it modify the internal structure of the protostar?
- Why are some discs/protostars showing jets while some others are not?
- How do close-in giant planets form and stop their inward migration?

Answering them requires coordinated studies involving both observations and simulations. Concerning observations, results from spectropolarimetric monitoring (involving in particular ESPaDOnS at CFHT and NARVAL at TBL) have demonstrated the wealth of new constraints that can be obtained about magnetospheric accretion processes operating between the protostar and its accretion disc on the one hand, and about the physics of magnetised accretion discs and associated outflows on the other hand. Now that the feasibility of the method is well established, time is ripe for a large-scale study on a significant sample of cTTSs and protostellar accretion discs; this is what the (recently submitted) MAPP Large Program with ESPaDOnS at CFHT is all about. Simultaneous coordinated observations with NARVAL/TBL (to complement ESPaDOnS observations and improve phase coverage), Phoenix/Gemini (nIR high resolution spectroscopy to study magnetic strengths from line broadening), multicolour broadband photometry (to provide additional information on activity phenomena), Chandra/XMM (to investigate the characteristics of the coronal and accretion plasma) and ALMA (to study the large-scale magnetic fields in collapsing clouds and in the outer regions of accretion discs) are also planned to obtain as complete a description as possible.

The MAPP program is associated with a worldwide effort in theoretical modelling involving in particular several leading groups in Europe, Canada and the USA. Numerical simulations of magnetised cloud collapse and magnetic discs are being carried out with improved physics and non-ideal MHD (eg ohmic and ambipolar diffusion, dust cooling, H2 dissociation, magnetic instabilities) as well as improved radiative transfer; computations also focus on the existence and properties of winds and outflows and will attempt describing the formation of the second protostellar core to find out what the initial conditions are for magnetospheric accretion phenomena. Magnetic coupling with the accretion disc and magnetospheric accretion processes are also being investigated through 3D MHD numerical simulations, implementing in particular more complex magnetic geometries and dynamo-active accretion discs to improve physical realism and obtain a better description of the angular momentum exchange between the protostar and its disc. Updated models of the internal structure of protostars, taking into account in particular the prior history of the pre-stellar core and the local accretion shocks occuring during the magnetospheric accretion stage, are also being worked on. Ultimately, comparing the observations and simulations should provide a new generation of stellar formation models that will be used to reevaluate the angular momentum evolution of young protostars.

In a more distant future, the whole research field would greatly benefit from having an ESPaDOnS-type spectropolarimeter that would operate in the nIR,

from 0.9 to 2.4 μm; it would in particular be an ideal tool for looking at much younger protostars that are still deeply embedded in their dust clouds (and thus totally out of reach of optical instruments), for investigating magnetic fields with increased sensitivity (the Zeeman effect being larger on nIR lines) and to access a larger number of accretion discs with cooler gas temperature in the innermost regions (mostly invisible or totally outshined at optical wavelengths). This is one of the main science drivers of the SPIRou (SpectroPolarimètre InfraRouge) project that we propose as a next generation instrument for CFHT.

This research (and the MAPP program) is one of the main research themes of the MagIcS international research initiative on stellar magnetic fields; it has been selected (and is thus partly funded) by the French Agence Nationale pour la Recherche (ANR) and is strongly supported by the Programme National de Physique Stellaire (PNPS) of CNRS/INSU (that we thank for its support) as one of its main priorities.

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